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INTEGRATED TURBINE WITH PM GENERATOR FOR SMALL HYDRO-POWER PLANTS

ZINTEGROWANA TURBINA Z GENERATOREM Z MAGNESAMI TRWAŁYMI DLA MAŁYCH ELEKTROWNI WODNYCH

Abstract

This paper presents a new concept of small hydropower plant with PM generator. This new solution has propeller turbine integrated with a PM generator. The turbine operates at variable speed and therefore the generator produces voltages at variable magnitude and frequency. For that reason the generated energy should be converted by a power electronics unit to fit the parameters of the external grid. Those three units: The turbine, the PM generator and the converter are described and the results of preliminary laboratory test are presented.

Keywords: Small Hydro Power Plants, Propeller turbine, PM generator

Streszczenie

W artykule przedstawiono nową koncepcje Małej Elektrowni Wodnej wyposażonej w generator z magnesami trwałymi. Zaprezentowano nowe rozwiązanie generatora z magnesami trwałymi zintegrowanego z turbiną śmigłową. Z uwagi na pracę turbiny przy zmiennej prędkości obrotowej generator wytwarza napięcia o zmiennej amplitudzie oraz częstotliwości. Konsekwencją tego jest konieczność zastosowania przekształtnikowego układu energoelektronicznego w celu przekształcenia i dopasowania parametrów generowanej energii do wymagań sieci. W pracy opisano oraz przedstawiono wyniki wstępnych badań laboratoryjnych dla trzech głównych elementów toru wytwarzania energii, tj.: turbiny śmigłowej, generatora z magnesami trwałymi oraz układu przekształtnikowego.

Słowa kluczowe: Małe Elektrownie Wodne, turbina śmigłowa, generator z magnesami trwałymi

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1. Introduction

Climate change due to CO_2 emission has been defined as the major environmental challenge to be faced nowadays by the international community. Hydropower is probably the most traditional and most important clean renewable energy source in Europe. The fuel of hydropower is running water, which mean rivers of any size, can be use, whilst the water still is available for any other purpose.

One GWh of electricity produced by Small Hydropower Plants (SHPs) means a reduction of CO_2 emission by 480 tones. On a global level there is no doubt about the benefits of converting energy by SHPs; climate change mitigation, security of energy supply. The same view can be taken on a regional level when making allowance for local development and employment.

2. Description of new solutions

Electrical generators for today's SHPs are designed as separate units. They work at constant rotary speed, which is kept by a speed controller often consisting of mechanical equipment. In this paper a concept of new type of electrical generator integrated with the propeller turbine will be described. It is assumed that the mechanical system for speed control by the angle of turbine blades will be removed, what leads to essential simplification of mechanical equipment and reduces the costs of SHP. The integration of the electrical generator with the propeller turbine rotor allows a reduction of the dimensions of the whole machine. The electrical generator has to be specially designed for such solutions because it should work in water. A synchronous generator excited by permanent magnets is a very promising solution [1, 2]. The rotating part of such generator, i.e. the rotor with permanent magnets will be located directly on the external surface of the propeller turbine. The stator of the generator, in 'classical' form will be located on stationary part i.e. in the housing of whole hydro-unit. However, both the rotor as well as the stator, and especially the stator windings, have to be protected from water. Such solutions are not used in hydropower technology [3]. Additionally, the rotation speed of propeller turbine will vary to insure the highest possible efficiency. It means that voltage magnitude of the generator will vary too, as well as its frequency. So, a power electronics unit has to be applied to insure the output frequency and voltages required by the electric power system and for control the power flow from generator to the grid. Application of a power electronic unit instead of a mechanical speed control, and control of the impeller blades, as in a Kaplan turbine, seems to be important advantage of the proposed solution because reliability of the power electronic units generally is much better than that of the blade control system utilized in Kaplan turbines. A waterproof solution for stator windings and permanent magnets on the rotor is needed and a cooling system of the generator must be included. So, existing knowledge of design of 'classical' hydro-generators and permanent magnet generators should be combined to achieve a new more efficient and more reliable hydro-generator.

Power technology with generators working at variable speed has been developed during the last decades for small wind mill power plants, but it is based on double fed asynchronous generators controlled by power electronics. Permanent magnet generators working at variable low speed for wind power technology are now developed. Requirements for wind- and hydro-generators differ so much, that permanent magnets generators for small hydro power plants should be independently developed. Exemplary small power plants with such generators both for wind and for water are now tested but the technology is still in progress [4, 5].

3. Propeller turbine integrated with PM generator

The hydro-set is based on a tubular turbine construction. Typical solutions utilize shaft based torque transfer systems to transfer load from a turbine impeller to a generator. Such systems tend to carry mechanical losses. However, solution proposed in this paper can overcome potential problems. The lack of a shaft based torque transfer system lets us simplify the hydro-set design and make it more compact, thus its failure frequency and susceptibility to vibration is lessened. We avoid the necessity of a shaft and a shaft guide system. The torque is transferred by a special external ring being an integrated part of the turbine impeller. This system is simple and durable and, therefore it requires no special service.

The Fig. 1 and Fig. 2 show a view and a cross-section of a complete hydro-set.

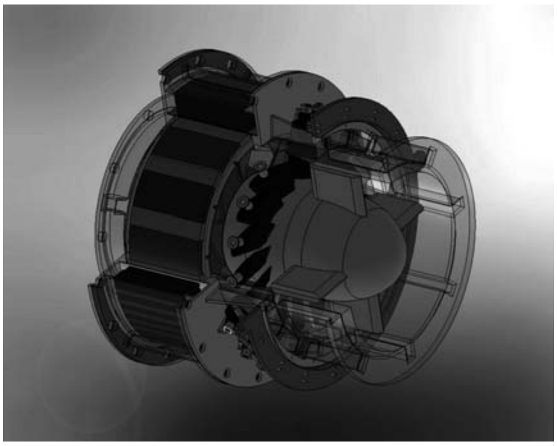

Fig. 1. View of a hydro-set
Rys. 1. Widok hydro-zestawu

Fig. 3 and Fig. 4 show location of a stator of the PM generator in the housing and location of permanent magnets on the rotor.

Materials used for a turbine should provide corrosion-resistant properties and, what is more important, anti-cavitating properties, so should be made from high quality aluminium-bronze, siliceous bronze or stainless steel. The blades of turbine are fixed to internal and external rings and allowed for work with rotation from 200 to 1000 rpm. Number of blades is related to the conditions of the localization the same as hub size or blade height. The goal is always the same to obtain heists efficiency.

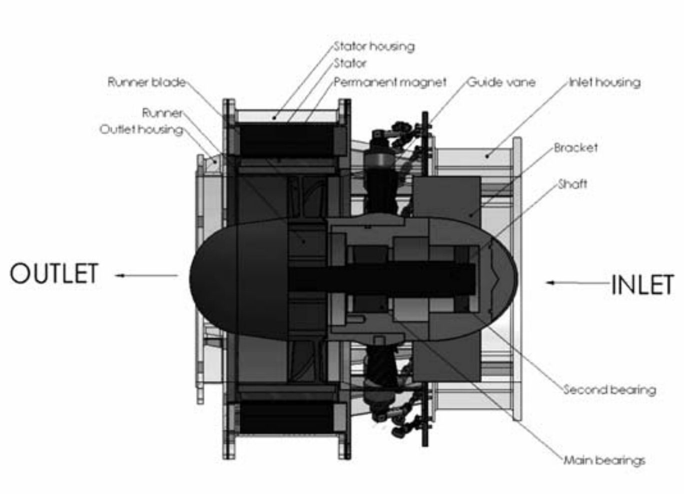

Fig. 2. Cross-section of a hydro-set
Rys. 2. Przekrój hydro-zestawu

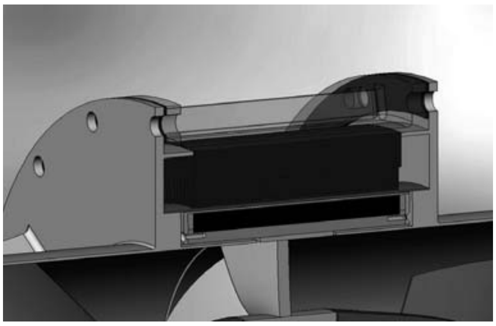

Fig. 3. View of stator location
Rys. 3. Położenie stojana

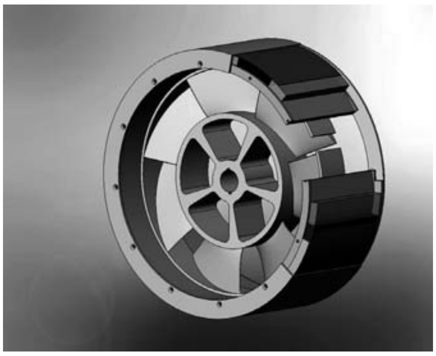

Fig. 4. Location of permanent magnets on the rotor
Rys. 4. Rozłożenie magnesów trwałych na wirniku

Permanent magnets are sticked to the external surface of the external ring and the spaces between magnets are filled with non-magnetic epoxide resin. Both internal surface of the stator and external surface of the rotor are protected by waterproof tubes. Water flow between rotor and the stator ensures generator's self-cooling system so that stator windings and permanent magnets are subjected to good cooling conditions.

The PM generator used in a hydro-set works at variable speed. Is should be specially designed considering to the range of speed and the structure of a power electronic converter. Its design should insure proper parameters of a generator, especially its internal reactance X_d and electromotive force EMF.

4. Power electronics units for SHPs

Due to the variable speed, the generated voltages have variable magnitude and frequency, which have to be adjusted to the voltage parameters of the electric grid to which PM generator is connected. It can be done by power electronics unit. Typically, AC/DC/AC frequency converters with DC link, i.e. so called back-to-back converters are used. There are many existing solutions of such converters and they are continuously in development. For SHPs with the hydro-unit described above, various solutions can be considered.

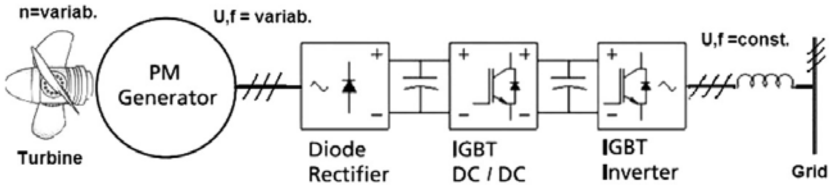

Fig. 5a. Scheme of a power electronics unit with DC/DC step-down and step-up in AC/DC converter
Rys. 5a. Struktura układu energoelektronicznego z prostownikiem diodowym, układem DC/DC oraz falownikiem IGBT

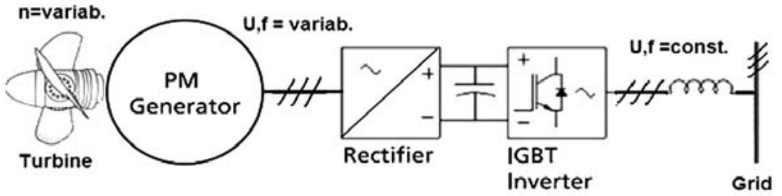

Fig.5b. Scheme of a power electronics unit with a thyristor rectifier or an active IGBT rectifier and an IGBT inverter
Rys. 5b. Struktura układu energoelektrycznego z sterowanym prostownikiem tyrystorowym lub sinusoidalnym prostownikiem IGBT oraz falownikiem IGBT

Any power electronics device able to stabilize level of DC voltage can be used as a AC/DC rectifier. It can be a very simple non-controlled diode rectifier combined with a DC/DC step-down and step-up converter, controlled thyristor rectifier or the most advanced – an active IGBT rectifier. All these converters are able to change the AC voltages with variable amplitude and frequency of a PM generator to the DC voltage. Above mentioned options are arranged according to optimization of wave forms of the PM generator current. For the first two types of AC/DC converters, the generator currents can contain higher harmonics. these harmonics lead to growing power losses in the stator windings and in the conducting elements of the rotor, but also alternating components of the electromagnetic torque are generated. An active IGBT rectifier is able to ensure sinusoidal waveforms and proper phase angles of generator currents, but it is the most expensive alternative.

The DC/AC inverter should have sufficient quality in order to ensure compability with the grid. Consequently the input DC voltages have to be permanently controlled and the work of the inverter has to be synchronized with the grid. Today's IGBT inverters are able to fulfil such requirements, producing almost sinusoidal currents with a proper phase to the grid. Various control strategies are used for that. To ensure better quality of energy transfer to the grid multi-level inverters can be used. They are however more expansive and require more advanced control systems. The multi-level inverters are still under development.

In Fig. 5a,b the structures of the power electronics units for SHPs are shown.

5. Laboratory tests of SHPs elements

So far the turbine and the PM generator and power electronics units have been tested separately.

The Turbine has been designed by the company CEDI, under a contract with the Norwegian company Turbinova AS. In order to investigate its performance, laboratory tests of scaled models have been carried out. The models had to comply with international standards and satisfy requirements of hydraulic and geometric similitude. To achieve hydraulic similitude the ratios of the various forces, acting between fluid and components had to be identical in both cases.

Model tests have been performed in accordance with the International Electrotechnical Commission (IEC 60193) requirements.

Testing program has been prepared and run in cooperation with Institute of Air, Process Engineering and Power Machines in Basic Construction and Fluid Machines of Wroclaw University of Technology. Stable conditions during the tests have been ensured.

Basic test conditions: H = 3m – ensured by natural water levels (upper reservoir (4) with a capacity of 4,5 m^3 and lower reservoir with a capacity of (11) 200m^3). A flow of Q = 0,09 – 0,16m^3/s is ensured by two propeller pumps (2) closing the circuit. In order to keep a constant Head, static pressure at the turbine inlet (6), was verified at each measurement point.

The turbine model has been manufactured from plastic, PC-ABS. Its mechanical properties are good for these kind of tests. Tensile strength equals 34.8 MPa, flexural strength equals 50 MPa. Parts made of plastic have been polished and painted to prevent water absorption. Rapid prototyping technology used to produce the runner, allowed the manufacture of advanced blade shapes in a short time.

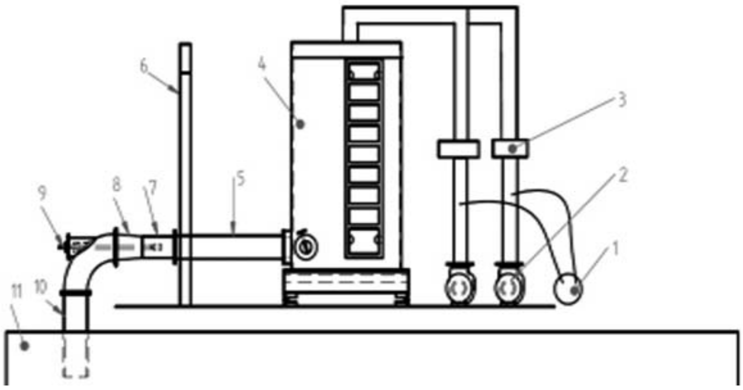

Fig. 6. Turbine test stand scheme
Rys. 6. Schemat stanowiska testowego turbiny

Fig. 7. Assembly of the turbine model
Rys. 7. Model turbiny po złożeniu

Figure 8 presents some of the obtained results, the generated power and the efficiency. The black curve shows the scaled up prototype turbine efficiency. The scaling is based on the model efficiency curve. Using Hutton's formula to calculate the best efficiency point of the prototype turbine.

$$\eta_T = 1 - (1 - \eta_M)\left[0.3 + 0.7\left(\frac{D_M}{D_T} \cdot \left(\frac{H_m}{H_P}\right)^{0.5}\right)^{\frac{1}{5}}\right] \tag{1}$$

where:

η_T – real turbine efficiency,
η_M – model turbine efficiency,
D_M – model turbine diameter,
D_T – real turbine diameter.

The rest points has been calculated using formula shown below

$$\eta_T = \eta_M \frac{\eta_{T_{MAX}}}{\eta_{M_{MAX}}} \tag{2}$$

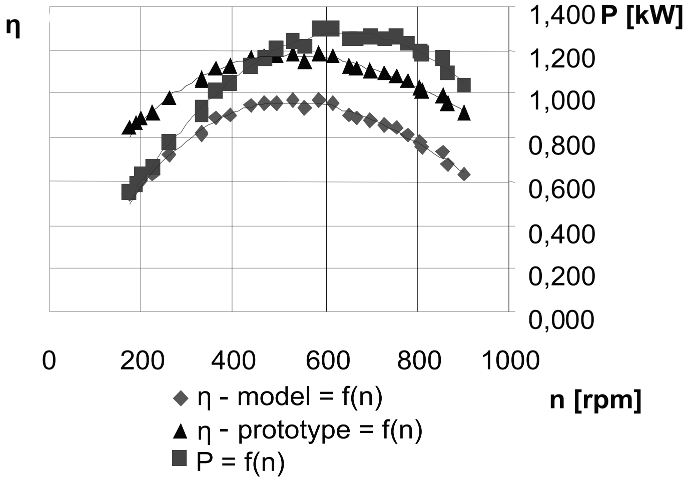

Fig. 8. Energetic characteristics
Rys. 8. Charakterystyki energetyczne

Fig. 9. Laboratory model of a PM generator working in water
Rys. 9. Laboratoryjny model generatora z magnesami trwałymi pracującego w wodzie

PM generator was designed in Poland for CEDI by KOMEL (Poland) and tests have been carried out at the Institute on Electromechanical Energy Conversion at Cracow University of Technology.

PM generator rated data: P_N = 2,2 kW; U_N = 500 V, I_N = 2,5 A; f = 50 Hz, n_N = 375 rpm.

The voltage characteristic for idle running generator is shown in Fig. 10. The speed has been changed from 110 rpm up to 610 rpm and at rated speed 375 rpm the rms value of phase voltage was 600 V.

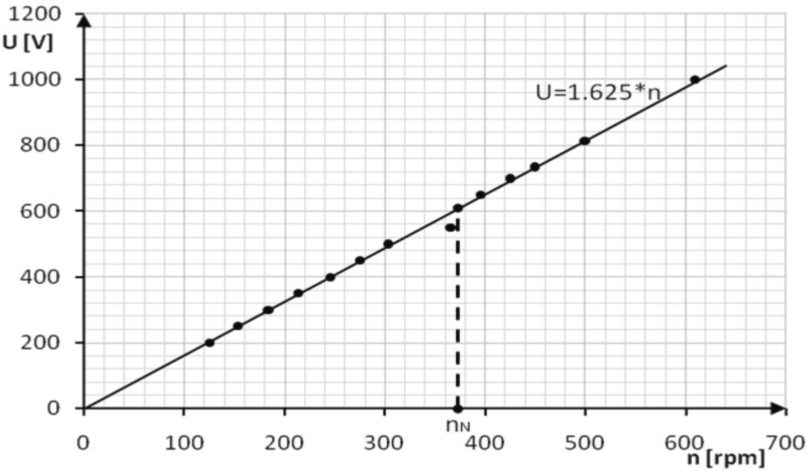

Fig. 10. Open-circuit characteristic
Rys. 10. Charakterystyka biegu jałowego

The wave-form of line voltage is presented in Fig. 11.

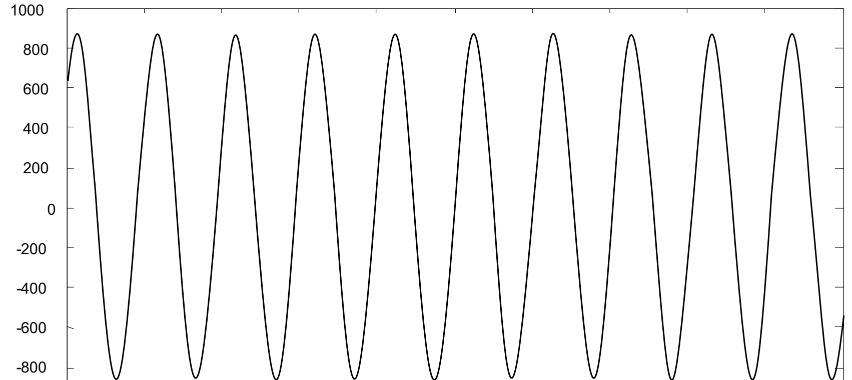

Fig. 11. Wave-form of line voltage generated by PM generator at 50 Hz
Rys. 11. Przebieg czasowy napięcia o częstotliwości 50 Hz wytwarzanego przez generator

The output characteristics for resistive load at different speeds are shown in Fig. 12. The output curves are linear but external voltages are decreasing rather fast with a level of the load. Internal voltage drop at rated current equals almost 20%, what is relatively big for PM synchronous generators.

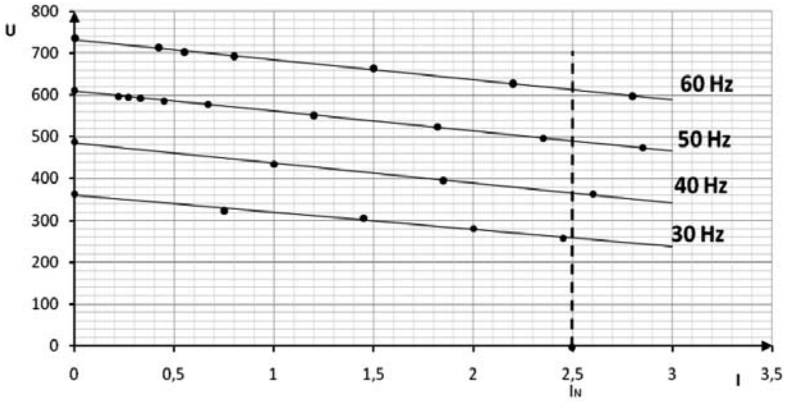

Fig. 12. External characteristics for resistive load
Rys. 12. Charakterystyki zewnętrzne dla obciążenia rezystancyjnego

Tested generator's resistance is R_s = 22 Ω and internal reactance is X_d = 39 Ω. Due to very high resistance the power efficiency at rated current was relatively low, η = 78%.

That generator was connected to the commercial 3-phase gird 400/230 V, 50 Hz by a back-to-back converter shown in Fig. 13. The tested converter has a simply uncontrolled diode rectifier as a AC/DC part, which limits the power flow control from a PM generator to the grid.

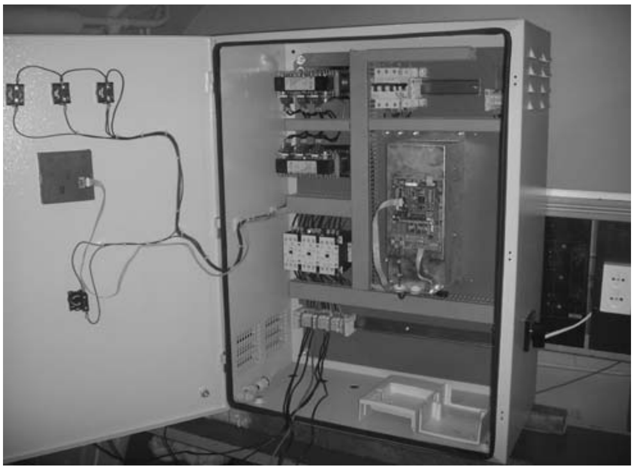

Fig. 13. Laboratory model of a back-to back converter
Rys. 13. Model laboratoryjny przekształtnika

At high speeds level of DC voltage was high enough to ensure that IGBT inverter output voltages were high enough to connect PM generator to the grid (400V) even at rated generator currents. At lower generator speeds the proper level of DC voltage can be achieved only at relatively low generator currents limiting the internal voltage drop in the generator. So, it was possible to transfer power from PM generator to the grid at limited speed and power intervals of the PM generator. In fact, speed and power control were possible due to big internal reactance and resistance of tested generator. For commercial applications both a PM generator with so big internal voltage drop as well as a back-to-back converter without DC voltage control cannot be accepted.

Figure 14 shows a wave-form of the PM generator line voltage after its synchronization to the grid. In comparison with waveform from Fig. 11 its shape essentially changes. It is almost rectangular and contains low frequencies mainly and it does not change with the load.

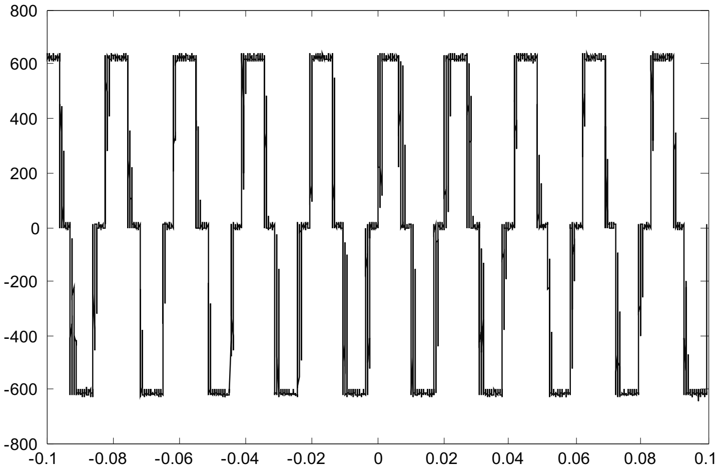

Fig. 14. Wave-form of the PM generator line voltage when connected to the grid
Rys. 14. Przebieg czasowy napięcia fazowego generatora po połączeniu i synchronizacji z siecią

Waveforms of phase currents both of the PM generator and the grid are shown in Fig. 15 and Fig. 16.

Both PM generator currents as well as the grid currents are distorted. The level of distortions depends on load. For higher loads the distortions are lower (see Fig. 15) and increased for lower loads (see Fig. 16).

The frequencies observed in all currents contain both frequencies characteristic for rectifier process as well as the frequencies of inverter control. PM currents contain mostly low frequencies harmonics characteristic of rectifier load. The higher harmonics increase the power losses but it seems to be not dangerous for generator windings. However, an input filter could be considered to improve generator performances.

The distortion of the grid currents has a different character and the grid currents contain rather high frequencies related to inverter control frequencies. For full load a level of distortions measured by THDi is acceptable by standards (THDi = 6.6%). However, in commercial applications an output filter should be applieded.

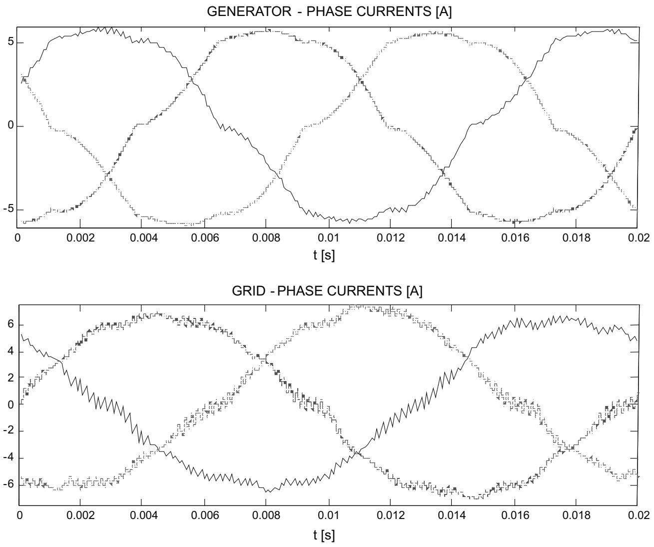

Fig. 15. Time domain waveforms of phase currents of the PM generator and the grid (high load: n = 462.7 rpm, fg = 61.7 Hz)

Rys. 15. Przebiegi czasowe prądów fazowych generatora oraz sieci (wysoki poziom obciążenia: n = 462,7 rpm, fg = 61,7 Hz)

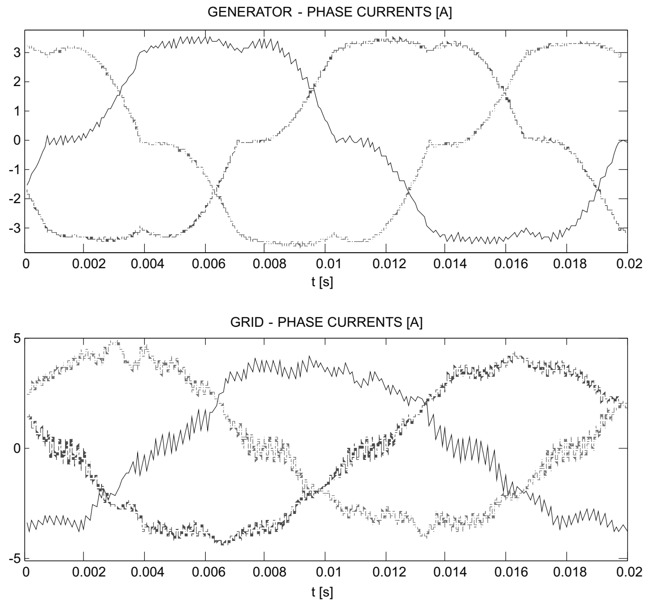

Fig. 16. Time domain waveforms of phase currents of the PM generator and the grid (low load at n = 394.5 rpm, fg = 52.6 Hz)

Rys. 16. Przebiegi czasowe prądów fazowych generatora oraz sieci (niski poziom obciążenia: n = 394,5 rpm, fg = 52,6 Hz)

6. Conclusions

The hydro-unit described in the paper has many advantages in comparison to classical hydro-generators with Kaplan turbines. The mechanical part of that hydro-unit is essentially simplified: a shaft does not exist, a transmission gear is not necessary and blades rotation control system is eliminated. All these facts bear significant impact on investment costs and reliability of the whole SHP.

The control of the power flow from water to the electric grid is provided by a power electronic converter. To do this, the PM generator has to be carefully designed. Its parameters should be chosen considering whole power transmission line, i.e. both dimensions of the propeller turbine as well as parameters and control strategy of the power electronics converter.

This paper shows that based on a Propeller turbine integrated with a PM generator and a power electronics converter, Small Hydropower Plants can effectively transfer available water energy to the electric grid with sufficient efficiency.

References

[1] Slemon G.R., *Electrical machines for variable- frequency drives*, Proc. of the IEEE, Vol. 82, No. 8, Aug. 1994, 1123-1139.
[2] Gieras J.F., Wing M., *Permanent Magnet Motor Technology Design and Applications*, Second Edition, Revised and Expanded, Electrical and Computer Engineering Series 2002, XVIII + 590 pp., MARCEL DEKKER, INC. New York Basel.
[3] Woditschka P., *Fortschritte durch Permanentmagnet-Technologie im Generatoren- und Motorenbau der 1MW-Leistungsklasse*, VDE-Kongress 2004, 18–20.10.2004, Berlin, Fach-tagungsberichte, Vol. 1, 409-414.
[4] Nerowski G., Kaufhold M., *Moderne elektrische Antriebstechnik-Herausforderungen, Innovationen*, Trends, VDE-Kongress 2004, 18–20.10.2004, Berlin, Fachtagungs-berichte, Vol. 1, 403-408.
[5] Binder A., Schneider T., *Permanent magnet synchronous generators for regenerative energy conversion - a survey*. EPE 2005. 11th European Conference on Power Electronics and Applications. 11–14.09. 2005, Dresden, Germany, 10.